Gulf and Caribbean Research

Volume 19 | Issue 2

January 2007

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Joshua K. Loefer
South Carolina Department of Natural Resources

George R. Sedberry
South Carolina Department of Natural Resources

John C. McGovern
NOAA Fisheries Service

DOI: 10.18785/gcr.1902.10

Gulf and Caribbean Research Vol 19(2), 83–88, 2007 Manuscript received November 17, 2006; accepted March 29, 2007

NOCTURNAL DEPTH DISTRIBUTION OF WESTERN NORTH ATLANTIC SWORDFISH (*XIPHIAS GLADIUS,* LINNAEUS, 1758) IN RELATION TO LUNAR ILLUMINATION

Joshua K. Loefer[1*], George R. Sedberry[1], and John C. McGovern[2]
[1]*South Carolina Department of Natural Resources, Marine Resources Research Institute, PO Box 12559, Charleston, South Carolina 29422-2559, USA*
**Corresponding author. Phone (843)953-9060, FAX (843)953-9820, E-mail loeferj@dnr.sc.gov*
[2]*NOAA Fisheries Service, 263 13th Avenue South, Saint Petersburg, Florida 33701 USA*

ABSTRACT Swordfish are known to undergo large diel vertical movements from surface waters at night to >300 m depth during the day. Evidence presented over the past several decades suggests the lunar cycle affects these vertical migrations. This study collected data concurrently from 7 swordfish throughout 3 consecutive lunar cycles using pop-up satellite archival tags. All individuals demonstrated an inverse relationship between recorded nocturnal depths and lunar illumination.

RESUMEN Los peces espadas son reconocidos por experimentar extensas migraciones verticales desde la superficie durante la noche, hasta aguas profundas (>300 m) durante el día. La evidencia presentada durante las pasadas décadas expone que el ciclo lunar afecta estas. Este estudio presenta la información que ha sido recopilada recientemente de 7 peces espadas durante 3 ciclos lunares consecutivos utilizando etiquetas de archivos que resurgen a la superficie y envían toda la información al satélite, conocidos en inglés como "pop-up satellite archival tags." Todos los individuos demostraron una relación inversa entre los datos obtenidos para profundidades documentadas en las horas nocturnas e.

INTRODUCTION

The swordfish (*Xiphias gladius*, Linnaeus, 1758) has a worldwide distribution in tropical, sub-tropical and temperate oceans, and its palatable flesh makes it a highly valued commodity throughout its range. The commercial importance of this species has lead to a substantial amount of research on life history, movements, stock identification, and bycatch issues (Ward et al. 2000).

Swordfish are known to undergo large diel vertical migrations characterized by descent to depths of up to 600 m or more during daylight hours and ascent to shallower waters at night (Carey and Robison 1981, Carey 1990). Therefore, most swordfish fisheries target the species at night when they are generally closest to the surface. Draganik and Cholyst (1988) and di Natale and Mangano (1995) noted variation in swordfish catch rates during the full moon in central Atlantic and Italian waters, respectively. de la Serna et al. (1992) found CPUE maximums during the new moon in the Strait of Gibraltar and adjacent Mediterranean and Atlantic waters. Moreno et al. (1991), however, found no relation between moonlight intensity and swordfish abundance, and Manday (1964) also concluded there was no lunar effect on depth-related catch in Cuban waters. Though some of these reports document changes in swordfish catch rate or abundance in relation to the lunar cycle, the methodologies used cannot provide demonstrative evidence that these variations are a direct result of behavioral changes in swordfish. Variations in CPUE or total catch may be due to designed or unintentional variation in depth of the fishing gear, changes in gear configuration related to tidal currents associated with lunar phase, visibility of bait that might be affected by lunar phase, or lunar periodicity in the behavior of the swordfish or its prey. Electronic tagging provides one of the best available methods to document vertical movements in large pelagic predators such as swordfish and investigate long-term (> 30 d) cyclical behavioral changes.

There have been several published studies on electronic tagging of swordfish (Carey and Robison 1981, Carey 1990, Sedberry and Loefer 2001, Takahashi et al. 2003). However, the study by Carey and Robison (1981) was the only one to mention changes in vertical movement patterns associated with the lunar cycle. They noted that of 6 swordfish tracked using acoustic telemetry, the 3 fish tracked during the full moon occupied deeper nocturnal depths than individuals tracked during other lunar phases. Limitations in study duration imposed by acoustic tracking, however, precluded tracking an individual specimen for an entire lunar cycle. Therefore, their observations on lunar differences had to be inferred from differences in behavior between different individuals, tracked at different times, and, in some cases, different locations.

Pop-up satellite archival tags (PSATs) allow for longer-term fishery independent data collection from highly-migratory fish species than was previously feasible. These devices allow researchers to collect large amounts of vertical movement data from individuals over large time

TABLE I

Tag deployment and pop-up information for all swordfish in the study. DAL = days at large (days from tag deployment to first satellite contact), LJFL = lower jaw fork length.

Tag ID#	Study interval (mos)	Deployment location	Deployment date	Pop-up location	Pop-up date	DAL	Est. LJFL (cm)
28662	1	32°6.4′N, 78°34.2′W	4/18/2002	32°19.6'N, 78°45.4′W	04/28/02	10	91
28663	1	32°2.8′N, 78°25.1′W	4/16/2002	34°17.6′N, 74°45.7′W	04/21/02	5	183
28664	1	32°4.0′N, 78°39.2′W	5/17/2002	32°21.2′N, 78°16.5′W	06/17/02	31	152
28665	1	32°3.4′N, 78°43.8′W	5/7/2002	35°2.0′N, 74°52.9′W	06/07/02	31	122
28666	2	32°4.5′N, 78°43.5′W	5/7/2002	34°31.6′N, 75°37.0′W	07/07/02	61	137
28668	2	32°0.0′N, 78°23.8′W	4/17/2002		No contact		112
28669	2	32°7.1′N, 78°33.3′W	4/18/2002	32°50.9′N, 77°28.7′W	04/27/02	9	213
28670	3	32°2.4′N, 78°41.3′W	5/17/2002	31°37.0′N, 78°29.8′W	08/17/02	92	107
28671	3	32°7.6′N, 78°32.1′W	4/17/2002	34°40.1′N, 75°32.9′W	04/25/02	8	102
30035	3	32°7.0′N, 78°40.9′W	5/7/2002	32°14.3′N, 78°5.6′W	05/12/02	5	122
30036	3	32°4.1′N, 78°24.5′W	4/16/2002	28°59.0′N, 79°58.1′W	07/16/02	91	81
30037	4	32°3.7′N, 78°37.2′W	4/17/2002	33°31.9′N, 75°14.6′W	04/23/02	6	107
30038	4	32°1.9′N, 78°42.4′W	5/16/2002	32°1.3′N, 79°0.0′W	09/16/02	123	107
30039	4	31°58.9′N, 78°45.8′W	5/7/2002	37°46.7′N, 70°51.6′W	08/17/02	102	122
30040	4	31°58.9′N, 78°45.8′W	5/7/2002	33°49.9′N, 76°30.2′W	05/16/02	9	122

periods without the need for recapture. This study presents PSAT data collected concurrently on several swordfish through 3 consecutive lunar cycles in the western North Atlantic.

MATERIALS AND METHODS

Swordfish were captured with pelagic longline gear deployed from a research vessel between 16 April and 17 May 2002. A total of 15 swordfish with estimated lower-jaw fork lengths from 81 to 213 cm were fitted with satellite pop-up tags. Tags were attached to the subjects by harpooning a 6.25 cm titanium M-type dart anchor into the dorsal musculature about 5 cm below the midline of the base of the dorsal fin. The anchors were inserted using a 20 cm titanium tagging needle protected by a 6 cm diameter rubber stopper that limited penetration depth to 12 cm. Tags were tethered to the anchors with 30 cm of 1.66 mm diameter fluorocarbon monofilament leader (100 kg tensile strength). Swordfish were not removed from the water during tagging, and were released by cutting the monofilament hook leader within a few cm of the hook.

Satellite pop-up tags (model PTT-100 Archival pop-up tag, manufactured by Microwave Telemetry, Inc., Columbia, MD, USA) were programmed to jettison at intervals of 30 (n=4), 60 (n=3), 90 (n=4) or 120 (n=4) days following tagging. The tags archived temperature and pressure readings once each hour until the release date was reached. A more complete description of the programming and function of the model PTT-100 PSAT can be found in Loefer et al. (2005).

Depth data retrieved from 7 of the 15 tags were combined and the resulting dataset was filtered so that only depth readings recorded between 0500 and 0900 GMT during the period of greatest temporal data overlap between individuals (8 May 2002 to 15 August 2002) remained. The 0500 to 0900 GMT timeslot was selected because depth data were consistently shallowest during this time period. A mean was calculated for each hourly timeslot in the filtered dataset. Each hourly mean was calculated from 2 to 7 concurrent depth readings from individual PSATs. These data were then compared to a corresponding lunar illumination schedule calculated by the United States Naval Observatory (http://aa.usno.navy.mil). Mean nightly depths were then regressed on percent lunar illumination and a correlation coefficient was calculated.

RESULTS

The 15 tags deployed in this study collected a total of 533 d of data while attached to the study animals, of which 462 d (87%) were retrieved via satellite. Six of the 15 tags stayed attached throughout the entire study interval and released on schedule. A total of 8 tags released before the

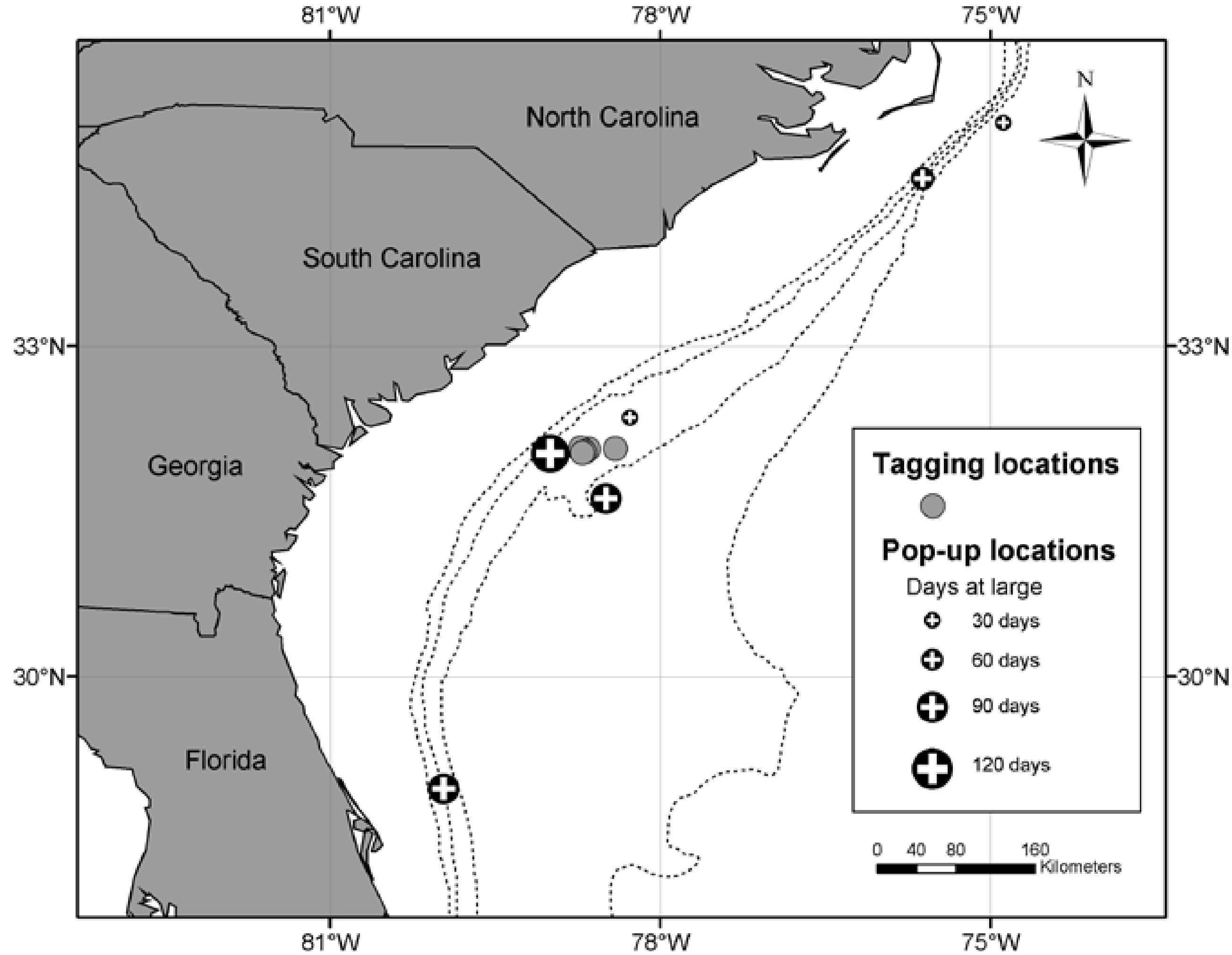

Figure 1. Swordfish tagging and tag pop-up locations ($n = 6$). Depth contours (from inshore to offshore) represent 100, 200, 500, and 1000 m.

scheduled date, and one tag never made satellite contact. Examination of data from the 8 early-release tags suggested that 3 were due to immediate post-release mortality, 4 were due to tag shedding (from 4 to 98 d after attachment), and the cause for the early release of one tag could not be determined from the recovered data (Table 1). Pop-up location data for the 6 full-retention tags indicated variation in general directions of movement. One fish moved south (360 km straight-line distance), 2 moved northeast (390 and 490 km), and 3 were within 50 km of the tagging location after up to 120 d at large (Figure 1).

Archived data from the 6 full-retention tags, as well as the tag which shed after 98 d of attachment, showed a strong pattern of diel vertical migrations. Swordfish occupied shallower waters from 0 to 160 m at night, and migrated to depths of 350 to 770 m during the day. They began to ascend from depth around 2–3 h before sunset (between 0000–0025 GMT in the study area), and they remained in near-surface waters for about 4–6 h. Swordfish usually began to descend before the first post-sunrise hourly record (sunrise: 1008–1040 GMT). The filtered (0500–0900 GMT) data demonstrated an inverse variation between mean nocturnal depths and percent lunar illumination throughout the 3-mo study period (Figure 2). Nocturnal depths recorded during periods of ≥ 90% lunar illumination ranged from 0 to 172 m with a mean of 77.0 m ($n = 443$), while depths recorded when lunar illumination was ≤ 10% were between 0 and 142 m with a mean of 34.3 m ($n = 408$, Figure 3). Linear regression of mean nightly depths on percent lunar illumination demonstrated a significant relationship ($n = 99$, $P < 0.001$) with a correlation coefficient of −0.66.

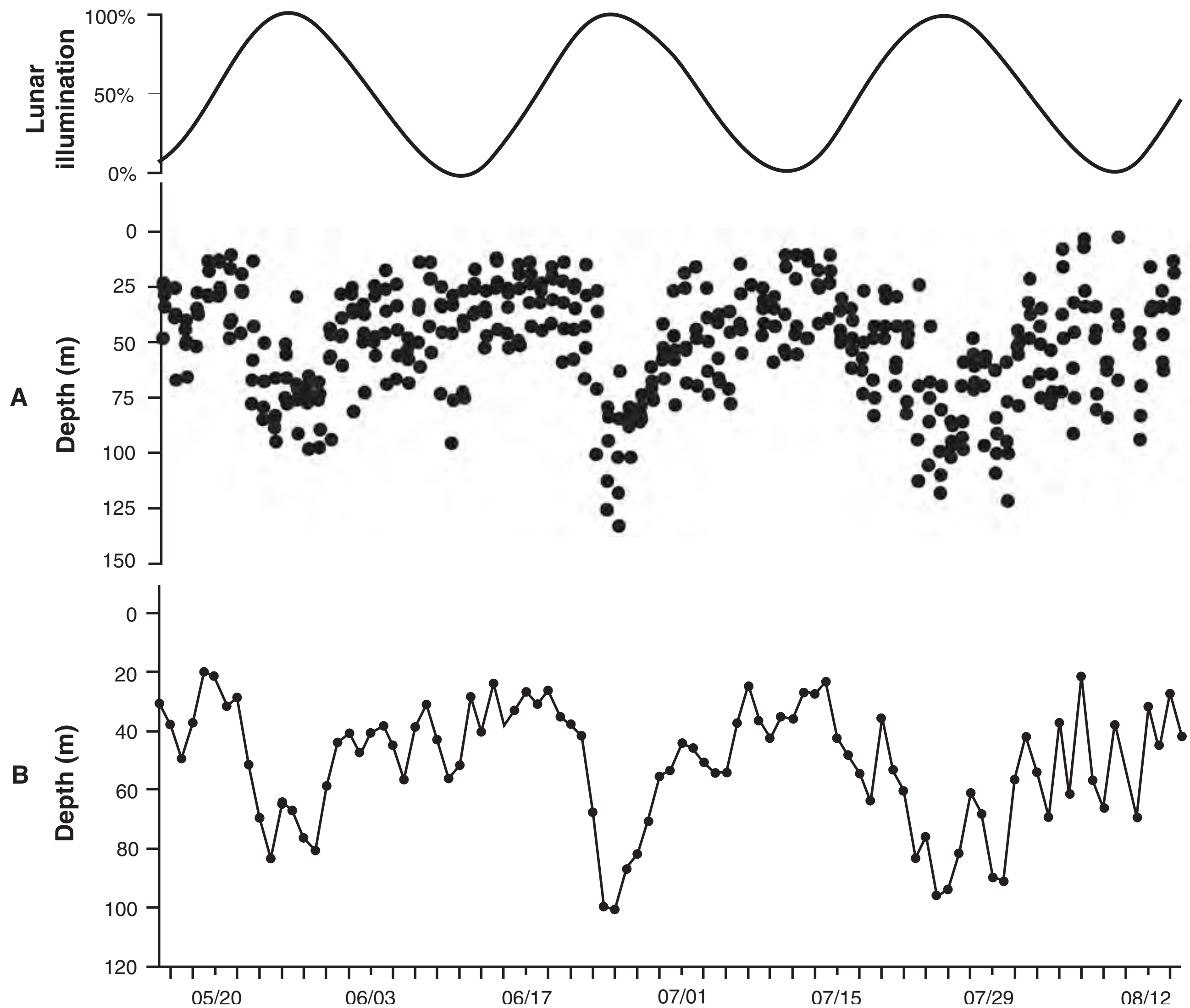

Figure 2. Lunar illumination schedule compared to (A) hourly mean of nocturnal depths (n = 501) and (B) nightly depth mean (n = 99).

DISCUSSION

Stillwell and Kohler (1985) found that swordfish diet in the western North Atlantic consists primarily of cephalopods (82% by frequency of occurrence) and teleosts (53%), many taxa of which are known to make nocturnal migrations into the shallow mixed layer to feed (Brodziak and Hendrickson 1999, Kinzer and Shulz 1985, Roper and Young 1975, Walker and Nichols 1993). Changes in nocturnal swordfish behavior, therefore, may be a result of active predation on vertically migrant midwater cephalopods and fishes. Swordfish may also follow isolumes to immerse themselves in an environment for which their eyes are adapted for maximum visual acuity and hunting success (Warrant 2004).

Regardless of the reason for these cyclical changes, the theory that swordfish follow isolumes and that their vertical migrations are affected by the lunar cycle is not new. It has long been considered common knowledge among commercial fishermen and fishery workers that swordfish are found further from the surface at night during the full moon than during other lunar phases. However, this conclusion has been based on data collected over a small time frame (less than one full lunar cycle, Carey and Robison 1981), on comparisons between different individuals observed at different times (Carey and Robison 1981), on analysis of CPUE data (Draganik and Cholyst 1988, Moreno et al. 1991, di Natale and Mangano 1995), or on anecdotal observations from fishermen (Manday 1964, di Natale and Mangano 1995). In contrast, the data for this study were collected concurrently from multiple individual fish throughout 3 consecutive lunar

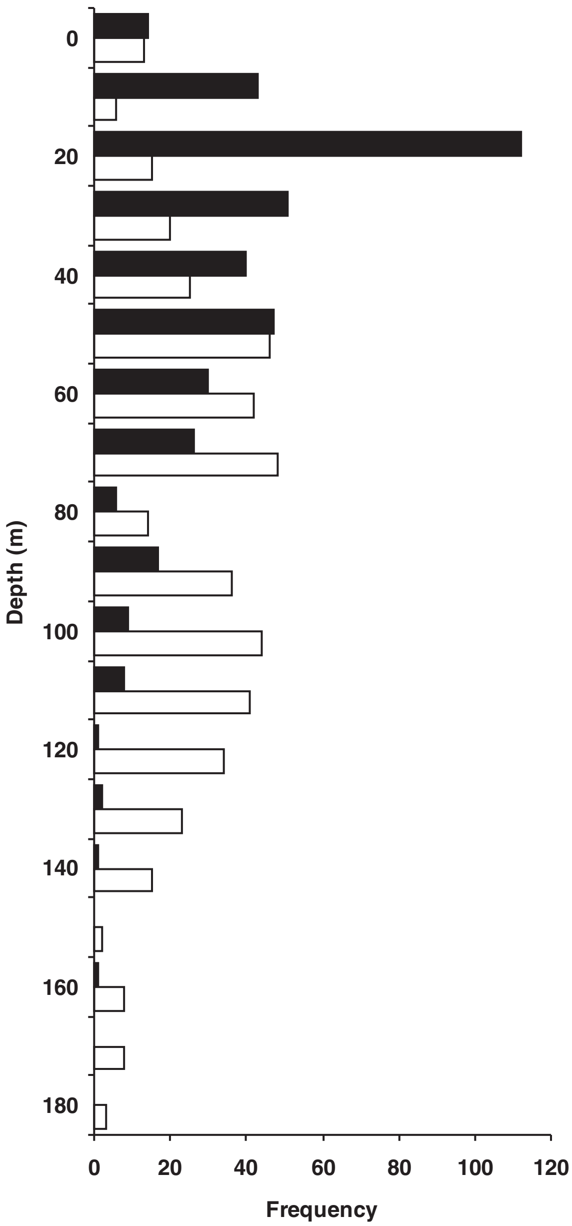

Figure 3. Depth frequency distribution for nocturnal depths (*n* = 851) recorded between 0500 and 0900 GMT during new moon (≤10% lunar illumination, black bars) and full moon (≥ 90% lunar illumination, white bars).

cycles. The described behavior was ubiquitous despite the movement of several animals away from the tagging area during the study. It is also interesting to note that the correlation between nightly depth and lunar illumination remained intact even when the moon was not visible in the study area (had not risen or had previously set) during the 0500 to 0900 GMT window examined. The data presented thus provide confirmation of the long accepted, yet unproven, theory that changes in nocturnal swordfish depth distributions are correlated with the lunar cycle.

Acknowledgements

We acknowledge the efforts of D.Russ, S. Meister, G. Ulrich, S. Burns, P. Mikell, B. White, D. Oakley, and the crew of the R/V *Palmetto* for field assistance. Constructive criticism of the manuscript was provided by M. Reichert and J. Geddings, while I. Bagnamanay La Torre Torres and G. Perez assisted with Spanish translation. The research described herein complies with all current laws and animal welfare policies of the United States. Permits for the capture and tagging of swordfish were provided by the US Department of Commerce, National Oceanic and Atmospheric Administration Office Sustainable Fisheries (Permit no. HMS-SRP-02-001). Funding was provided by NOAA Fisheries grant numbers NA07FL0497, NA16FL2814, and NA03NMF4720321 (G. Sedberry, Principal Investigator). This is Contribution Number 583 from the South Carolina Marine Resources Center.

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